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CONCEPT DEFINITION: RETIREMENT FOR CAUSE OF F100 ROTOR COMPONENTS

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Final Report for Period June 1979 Through March 1980

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This technical report has been reviewed and is approved for publication.

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Historically, gas turbine engine disks are retired when they accrue an analytically determined lifetime where the first fatigue crack per 1000 disks could be expected. By definition then, 99.9% of these components are being retired prematurely. Retirement-for-cause (RFC) is a procedure, based on Fracture Mechanics, which would allow safe utilization of the full life capacities of each individual disk. Since gas turbine disks are among the most costly of engine components, adopting a RFC philosophy could result in substantial systems life cycle cost savings. These would accrue from reduced replacement costs, conservation of strategic materials such as cobalt, and energy savings. This study addresses the application of this concept to the USAF F100 engine.

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FOREWORD

This work was performed under Materials Laboratory Contract F33615-76-C-5172 with the Project, Task Area and Work Unit Numbers assigned as 7351 06 C1. The Air Force project manager was Dr. W. H. Reimann, AFWAL/MLLN, and the work was conducted in the Materials and Mechanics Technology Laboratories of Pratt & Whitney Aircraft Government Products Division, West Palm Beach, Florida. The Program Manager was J. A. Harris, Jr., reporting to M. C. VanWanderham, Mechanics of Materials and Structures. D. H. Nethaway and C. G. Annis, Jr., were Deputy Program Managers, and D. L. Sims was the Program Coordinator.

The program was jointly sponsored by Dr. Michael Buckley of the Defense Science Office, Defense Advanced Research Projects Agency, and the Materials Laboratory of the Air Force Wright Aeronautical Laboratories. Dr. Buckley's and the many AFWAL participants contributions to the program are acknowleeged. The authors also wish to acknowledge J. S. Cargill, and J. E. Doherty, for their contributions in the field of Nondestructive Evaluation, and E. J. Reed and F. J. Staudt for the Life Cycle Cost Analyses.

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SUMMARY

Total fatigue life of a component consists of a crack initiation phase and a crack propagation phase. Engine rotor component initiation life limits are analytically determined using lower bound (1 occurrence in 1000) LCF characteristics. By definition then, 99.9% of the disks are being retired prematurely. Retirement for Cause (RFC) would allow each component to be used to the full extent of its safe total fatigue life, retirement occurring when a quantifiable defect (as determined by nondestructive evaluation techniques — NDE) necessitates removal of the component from service. The defect size at which the component is no longer considered safe is determined through fracture mechanics analyses of the disk material and the disk fracture critical locations, the service cycle and the overhaul/inspection period. Realization and implementation of a Retirement for Cause Maintenance Methodology will result in system cost savings of two types: direct cost savings resulting from utilization of parts which would be retired and consequently require replacement by new parts; and indirect cost savings resulting from reduction in use of strategic materials, reduction in energy requirements to process new parts, and mitigation of future inflationary pressure on cost of new parts.

This study evaluated the rotor components of the United States Air Force F100 gas turbine engine. For the 15-yr average engine system life assumed, Retirement for Cause is applicable to 21 individual rotor components, and would result in engine life cycle cost savings of $249 million.

An estimated investment of $16 million for technology development, nondestructive evaluation system development, facilities, equipment and training is required to enable implementation at a USAF Air Logistics Center in January 1985.

Thus, an investment of $16 million in the period 1980-1984 yields a return of $249 million in the period 1985 through 2000. This is an annual Return on Investment (ROI) of approximately 50% for Retirement for Cause for the USAF F100 engines over the 20-yr time period.

SECTION I

INTRODUCTION

A. BACKGROUND

Historically, methods used for predicting the life of gas turbine engine rotor components have resulted in conservative estimation of useful life. Most rotor components are limited by low cycle fatigue, generally expressed in terms of mission equivalency cycles. When some predetermined cyclic life limit is reached, components are retired from service. These cyclic life limits are established by a statistical analysis of data indicating the cyclic life at which 1 in 1000 disks will have a fatigue-induced crack of approximately 0.03-in. length. It has been documented that many of the 999 remaining disks, which are also retired at the same time, have considerable useful residual life. Retirement for Cause (RFC) provides a Fracture Mechanics and Nondestructive Evaluation (NDE) based procedure for screening the one bad part and certifying the remaining 99.9% for additional safe engine service.

The fatigue process for a typical rotor component such as a disk can be visualized as illustrated in Figure 1. Total fatigue life consists of a crack initiation phase followed by growth and linkup of microcracks. The resulting macrocrack(s) would then propagate subcritically until the combination of service load (stress) and crack size exceeded the material fracture toughness. Catastrophic failure would result had not the component been retired from service. To preclude such cataclysmic disk (and possibly engine) failures, disks are typically retired at the time where 1 in 1000 could be expected to have actually initiated a short (0.03 in.) fatigue crack. By definition 99.9% of the retired disks still have useful life remaining at the time they are removed from service. Under the Retirement-for-Cause philosophy, each of these disks could be inspected and returned to service. The return-to-service (RTS) interval is determined by a fracture mechanics calculation of remaining propagation life from a crack just small enough to have been missed during inspection. This procedure could be repeated until the disk has incurred measureable damage, at which time it is retired for that reason (cause). Retirement for cause is a methodology under which an engine component would be retired from service when it had incurred quantifiable damage, rather than because an analytically determined minimum design life had been reached. Its purpose is *not* to extend the life of a rotor component, but to utilize safely the full life capacity inherent in that component.

The Metals Behavior Branch of the Materials Laboratory (AFML/LLN — now AFWAL/MLLN) has been conducting in-house research and development activities in the RFC area since 1972. Pratt & Whitney Aircraft Group began extensive research and development programs under corporate, IR&D, and Government contract sponsorship in 1972 to identify and develop the applied fracture mechanics and NDE technologies necessary to realize the RFC concept. The program effort reported herein, "Concept Definition: Retirement for Cause of F100 Rotor Components," is the first to consolidate and focus these technologies on a specific system and to quantify the benefits and risks involved.

B. F100-PW-100 TURBOFAN ENGINE

1. Introduction

The USAF F100 engine built by Pratt & Whitney Aircraft, is an augmented (afterburning) turbofan engine in the 25,000-lb thrust class with a thrust-to-weight ratio in excess of 8 to 1. This engine currently powers the F-15 and F-16 fighters. It has amassed more than 450,000 operational flight hours with the USAF Tactical Air Command (TAC) since becoming operational in the F-15 aircraft at Luke Air Force Base, Arizona. The engine is currently in operational *service around the world in the twin-engine* McDonnell Douglas F-15 and the single engine General Dynamics F-16 fighter aircraft shown in schematic form in Figure 2. It is anticipated that in excess of 3100 engines will be in the USAF operational inventory.

The F100 has been subjected to the most severe series of durability tests in U. S. aviation history. Since completing the official 150-hr Qualification Test in October 1973, the engine has accomplished seven 150-hr substantiation tests, a 150-hr test at overtemperature conditions, a 3,000-cycle low-cycle fatigue test, a 1,300-hr Accelerated Mission Test (AMT), a 2,000-hr Accelerated Mission Test tailored to the mission of the F-15 fighter, and a 2,000-hr Accelerated Mission Test tailored to the mission of the F-16 fighter. The purpose of the AMT is to improve engine durability throughout its service life by identifying potential problems, developing improvements, and implementing changes at the earliest possible time in the engine production program. AMT testing will continue throughout the service life of the engine, as component and/or mission changes occur. It is anticipated that the Retirement for Cause methodology will be demonstrated in an AMT prior to implementation.

2. Engine Description

The F100 is an axial flow, low-bypass, high-compression ratio, twin-spool engine with an annular combustor and common flow augmentor. It has a three-stage fan driven by a two-stage (low-pressure) turbine and a 10-stage compressor driven by a two-stage (high-pressure) turbine.

The engine is equipped with a lightweight, variable, convergent-divergent nozzle based upon the balanced-beam concept. Nozzle area setting is a function of the engine control, such that near optimum performance is provided at all operating conditions. The engine and its salient features are shown in Figure 3.

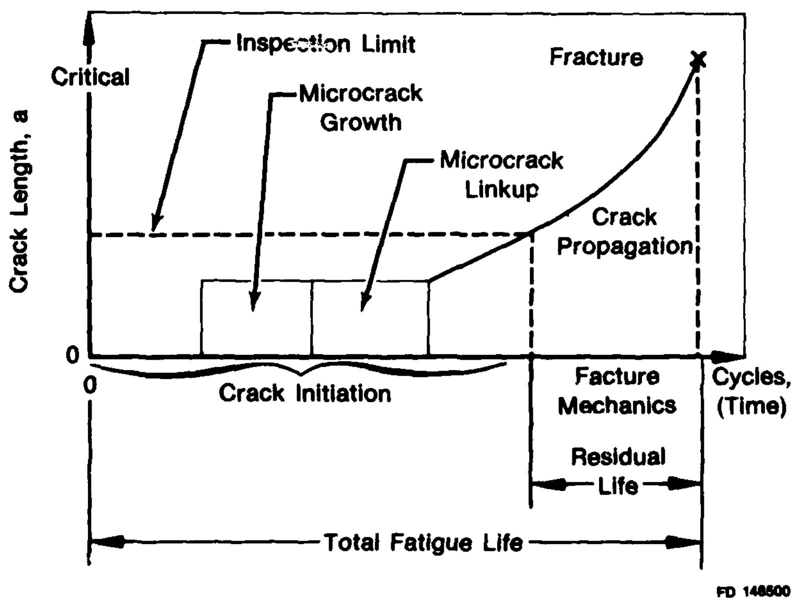

Figure 1. Total Fatigue Life Segmented Into Stages of Crack Development, Subcritical Growth, and Final Fracture

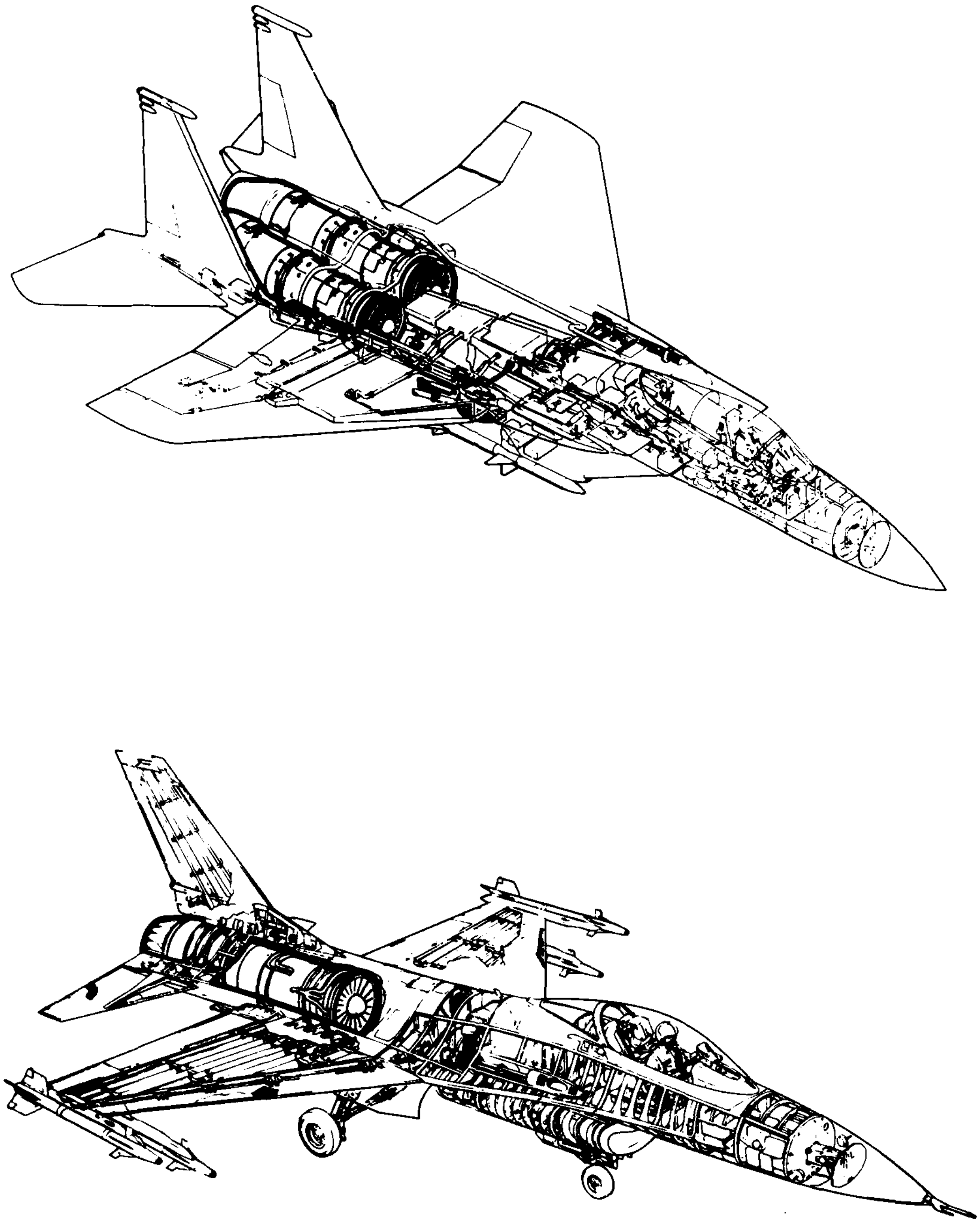

Figure 2. F100 Engine Installation in the F-15 (Top) and F-16 (Bottom) Fighter Aircraft

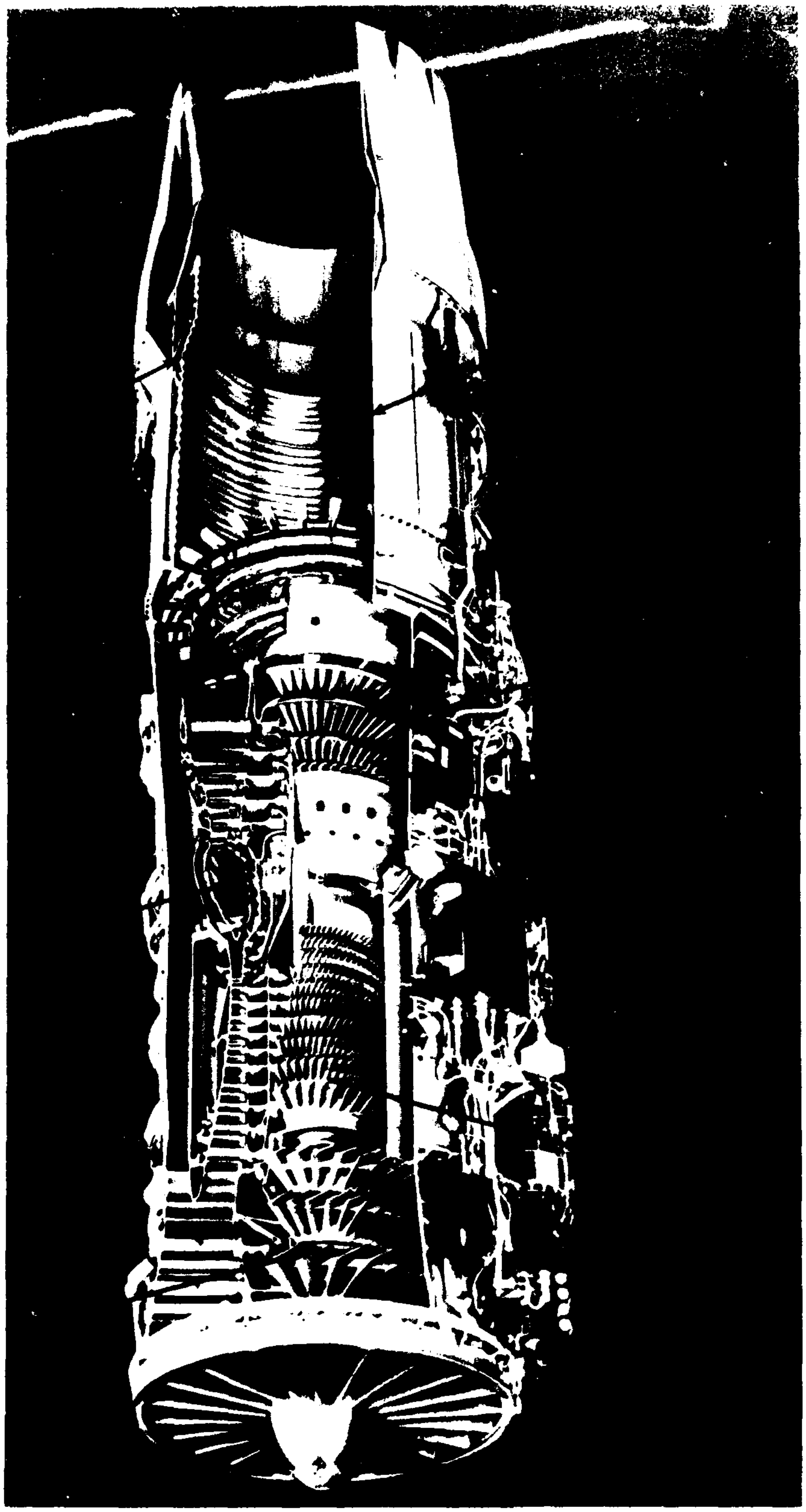

Figure 3. F100-PW-100 Turbofan Engine

The engine consists of five major modules: fan; core (compressor, combustor, and compressor-drive turbine); fan-drive turbine; augmentor and exhaust nozzle; and the gearbox. The modular configuration is shown in Figure 4. Each module is completely interchangeable from engine-to-engine at the intermediate maintenance level.

The modular approach was selected for the F100 engine so that parts associated either functionally or physically can be removed as units. Modular construction has resulted in a reduction in the cost of maintaining the engine.

3. Candidate Retirement for Cause Components

The fan, core, and the fan-drive turbine contain the components considered for RFC in this program. The core consists of two major rotating assemblies, the compressor (HPC) and the compressor-drive turbine (HPT), and each of these are considered separate modular items for the RFC maintenance concept in this report. Therefore, the fan, compressor (HPC), high-pressure turbine (HPT), and fan-drive turbine (LPT) contain the 27 candidate components considered for RFC. Table 1 lists the candidate components and their materials.

C. PROGRAM OPERATION

The technical tasks of this program were accomplished in the time period of June 1979 through January 1980 by a technical project group assembled from the Engineering, Product Support and Product Integrity Departments of the Pratt & Whitney Aircraft Group, Government Products Division, organized and managed by the Mechanics of Materials and Structures Unit. During the program, three program reviews were held for purposes of evaluation, critique and technical guidance by selected advisors from the Government, industrial (including P&WA management) and academic communities. The reviews were conducted in two phases: a Steering Group Session followed by an Executive Group Session. The purpose of the reviews was to focus the expertise and attention of those agencies and individuals responsible for technology development, engine development, and system maintenance and operation upon the application of Retirement for Cause to the F100 engine. The Project Group provided detailed presentations of the work performed to the Steering Group; the Steering Group discussed the work and made recommendations to the Executive Group; the Executive Group review of the presentations and recommendations resulted in and/or confirmed the technical direction, decisions and conclusions of the program. In addition to the primary objective of providing technical and managerial guidance to the program, the program review group had three secondary objectives:

- To ensure this concept definition program fully addressed all appropriate areas;
- To ensure continuing awareness and coordination throughout U. S. Air Force (and appropriate Government) organizations;
- To assist in future phases of RFC activities if applicable.

The organizations, agencies or individuals represented on the Steering and Executive Groups and participating in the program reviews are listed in Table 2.

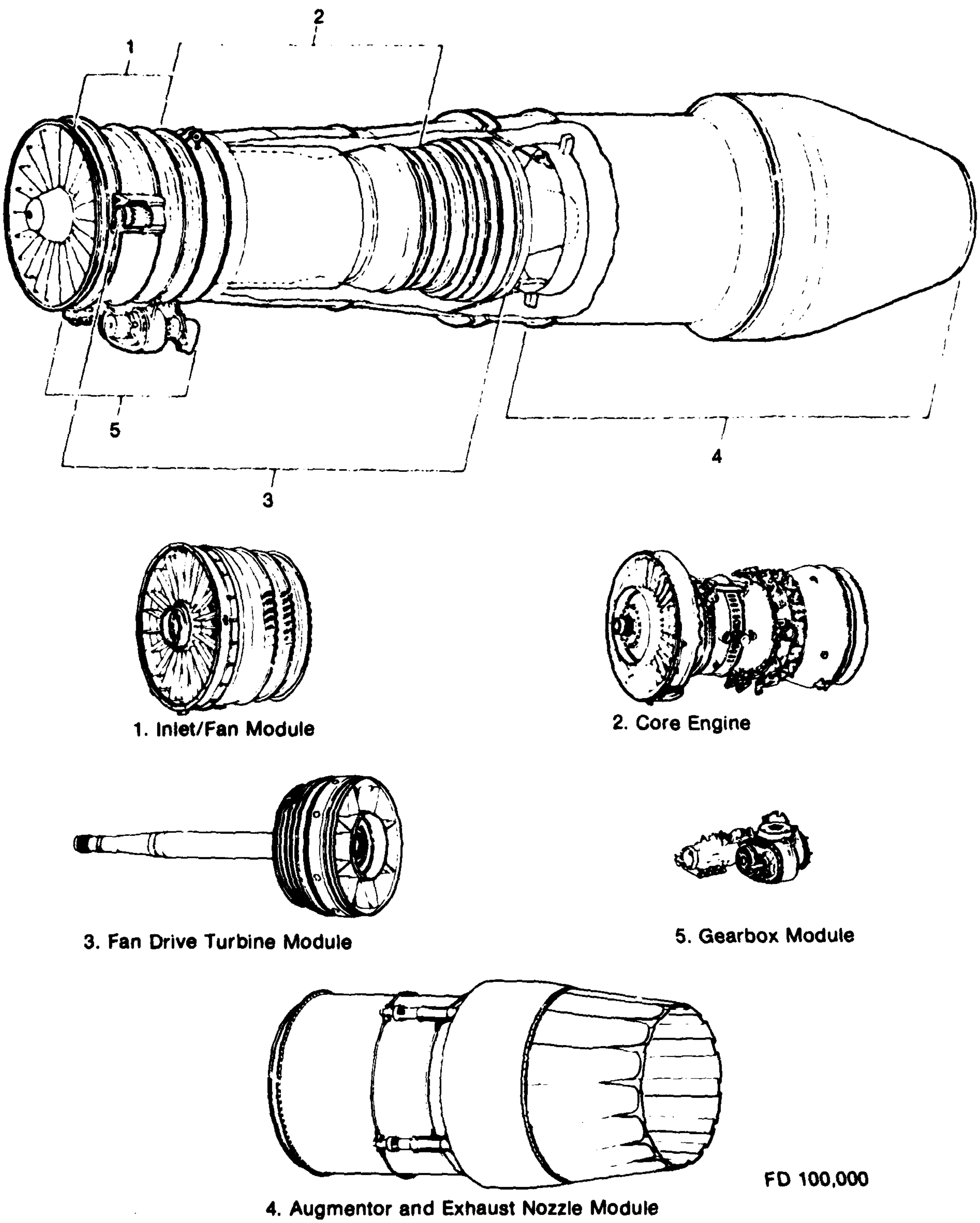

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Figure 4. Modular Configuration of the F100 Engine

TABLE 1. F100 ENGINE RETIREMENT FOR CAUSE CANDIDATE ROTOR COMPONENTS

Module	*Component Name*	*Material**
Fan	1st Stage Disk and Hub	Titanium 6-2-4-6
	2nd Stage Disk and Hub	Titanium 6-2-4-6
	3rd Stage Disk	Titanium 6-2-4-6
	2nd Stage Air Seal (2-3 Spacer)	Titanium 6-2-4-6
Compressor (HPC)	4th Stage Compressor Disk	Titanium 6-2-4-6
	5th Stage Compressor Disk	Titanium 6-2-4-6
	6th Stage Compressor Disk	Titanium 8-1-1
	7th Stage Compressor Disk	Waspaloy
	8th Stage Compressor Disk	Waspaloy
	9th Stage Compressor Disk	IN-100
	10th Stage Compressor Disk	Waspaloy
	11th Stage Compressor Disk	IN-100
	12th Stage Compressor Disk	Waspaloy
	13th Stage Compressor Disk	IN-100
	6th Stage Air Seal (6-7 Spacer)	Waspaloy
	7th Stage Air Seal (7-8 Spacer)	Waspaloy
	8th Stage Air Seal (8-9 Spacer)	Waspaloy
	9th Stage Air Seal (9-10 Spacer)	Waspaloy
	10th Stage Air Seal (10-11 Spacer)	Astroloy
	11th Stage Air Seal (11-12 Spacer)	Astroloy
	12th Stage Air Seal (12-13 Spacer)	Astroloy
Compressor Drive Turbine (HPT)	1st Stage Turbine Disk	IN-100
	2nd Stage Turbine Disk	IN-100
	1-2 Rim Spacer	IN-100
	1st Stage Front Blade Retaining Plate (TOBI Seal)	Astroloy
Fan Drive Turbine (LPT)	3rd Stage Turbine Disk	IN-100
	4th Stage Turbine Disk	IN-100

*All Materials in Wrought Form

TABLE 2. PROGRAM REVIEW GROUP MEMBERSHIP*

Executive Group	*Steering Group*
Chairman — W. H. Reimann, USAF Project Manager	All Members of Executive Group
Defense Advanced Research Projects Agency Defense Science Office (DSO)	Air Force Wright Aeronautical Laboratories Working Group
Air Force Wright Aeronautical Laboratories Materials Laboratory (AFWAL/ML) Aero Propulsion Laboratory (AFWAL/PO)	Air Force Acquisition Logistics Division
USAF Aeronautical Systems Division F100 Joint Engine Project Office (ASD/YZ100) Flight Systems Structures Division (ASD/ENFS) Logistics Engineering Division (ASD/YZLE) Structural Durability Division (ASD/YZES)	P&WA/GPD — Government Products Division Senior Engineering Department Management Program Project Group Product Support Department Product Integrity Department Marketing Department
Air Force Logistic Command/San Antonio Air Logistics Center Materials Management Propulsion Reliability (SAALC/MMPR) Materials Management Engineering Test (SAALC/MMET)	P&WAG - Commercial Products Division
Technical Consultants H. Liebowitz — George Washington University C. A. Rau — Failure Analysis Associates C. H. Wells — Southwest Research Institute J. N. Yang — George Washington University	P&WAG - Manufacturing Division

*Agencies/or individuals represented.

SECTION II

RESULTS

A. PROGRAM OBJECTIVE

The objective of this program was to determine the feasibility of applying a Retirement-for-Cause (RFC) maintenance approach to the F100 engine. The study was directed primarily toward rotating components of that engine, specifically the various disks and airseals/spacers that comprise the prime rotor structure. The technical effort consisted of the five tasks outlined below:

- Define an RFC Methodology and a means of assessing the ROI for its application
- Evaluate the disks of the F100 engine plus other appropriate engine rotor components for RFC applicability
- Assess nondestructive evaluation (NDE) requirements for implementation
- Establish a ranking of components for development priorities
- Establish development plans leading to implementation.

The results of this technical effort are discussed in the following sections of this report.

B. RETIREMENT FOR CAUSE METHODOLOGY

1. Introduction

All fatigue data have inherent scatter. The data base used for design life analyses purposes must be applicable to all disks of a given material, and therefore includes test results from many heats and sources. Data are treated statistically as shown schematically in Figure 5. The distribution of life, defined as the number of cycles necessary to produce a crack approximately 0.03 in. long, is obtained for a given set of loading conditions (stress/strain, time, temperature). As can be seen, the $\pm 2\sigma$ bounds, which contain 95% of the data, may span two orders of magnitude in fatigue initiation life.

When considered with other uncertainties in any design system (e.g., stress analysis error, field mission definition, fabrication deviations, temperature profile uncertainty) the final disk life prediction is made for disk crack initiation life for an occurrence rate of 1 in 1000 disks. It is at this life that all LCF-limited disks are removed from service. This procedure has been very successful in preventing the occurrence of catastrophic failure of disks in the field. However, in retiring 1000 disks because one may fail, the remaining life of the 999 unfailed disks is not utilized. The amount of usable life remaining can be significant, as shown in Figure 6, where over 80% of the disks have at least 10 lifetimes remaining.

The means of extracting the remaining useful life from each disk must be safe to avoid catastrophic failure. This is done by determining the disk crack propagation life (N_p) (at every critical location) from a defect barely small enough to be missed during inspection. The Return-to-Service (RTS) interval is then calculated by conducting a Life Cycle Cost (LCC) analysis to determine the most economical safety factor (SF) to apply to N_p (RTS interval = N_p/SF). Cost vs SF is plotted for each individual disk and combined to determine the most economical interval to return a module for inspection. An example is shown in Figure 7.

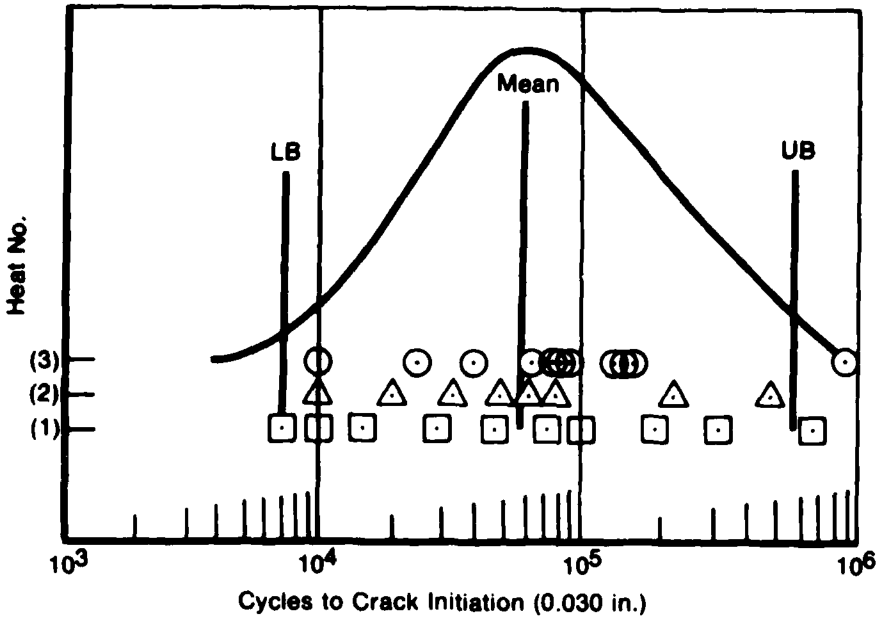

Figure 5. Material Data Scatter Results in Conservative Life Prediction

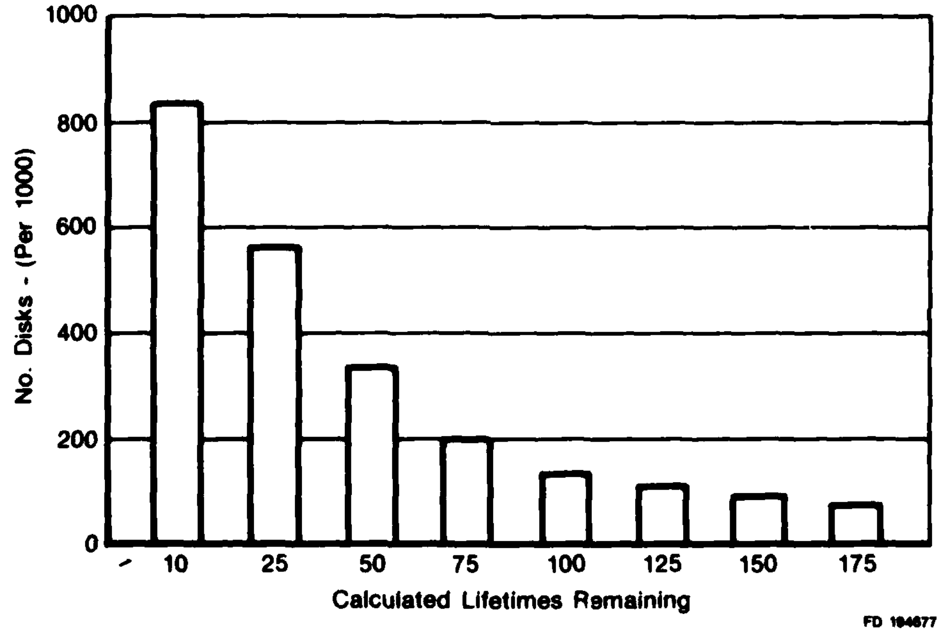

Figure 6. The Majority of Disks Have Useful Life After Retirement

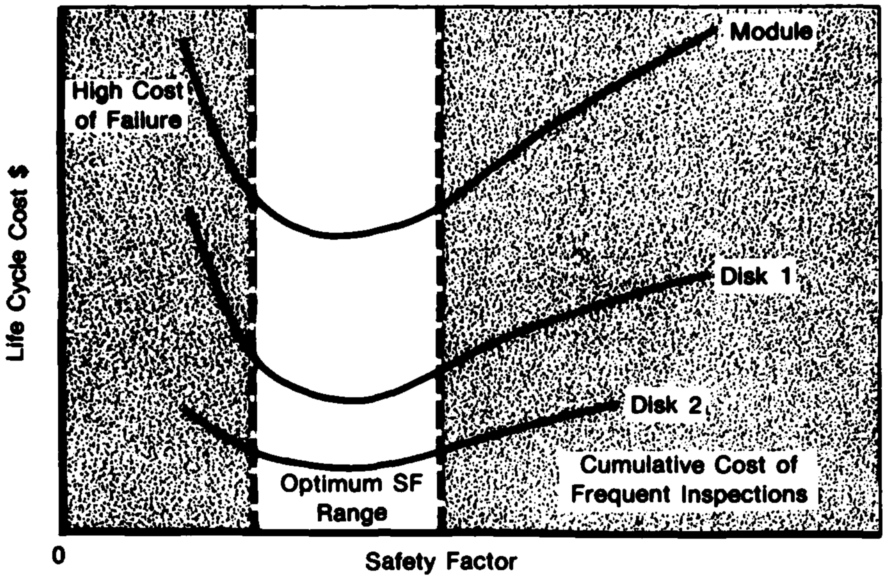

Figure 7. Safety Factor Is Determined from an Economic Balance Between High Cost of Failure vs Cumulative Costs of Frequent Inspections

The first required disk inspection is near the end of the analytically determined crack initiation life. Only one disk in 1000 inspected should have a crack and be retired. The other 999 will be returned to service for the calculated RTS interval. This inspection is repeated at the end of each RTS interval with the cracked disks being retired and all others returned to service. Figure 8 illustrates how the residual life is extracted from each disk after the crack initiation life has been used.

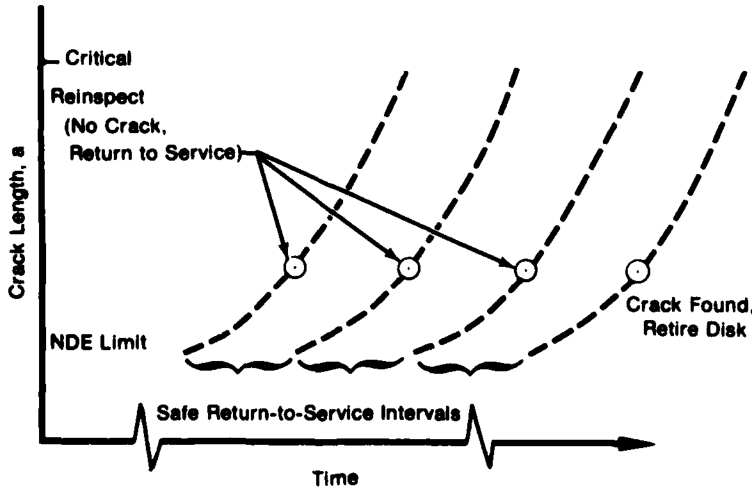

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Figure 8. Base Retirement for Cause Concept

As Figures 7 and 8 illustrate, Return-to-Service intervals are based on two broad technologies: Nondestructive Evaluation (NDE) and applied Fracture Mechanics, and evaluated based upon economic factors.

Fracture Mechanics must provide an assessment of the behavior of a cracked part should it pass NDE with a defect just below the inspection limit. To assure safe return to service of a part which *may* contain a small crack, an accurate crack propagation prediction is imperative. Recent strides in applied elevated temperature fracture mechanics (References 1, 2, 3, and 4) have provided the necessary mathematical description (models) of basic propagation, i.e., crack growth under conditions of varying loading frequency (υ), stress ratio (R), and temperature (T). Further work (References 5 and 6) has expanded this capability to include loading spectra synergism, i.e., crack growth subjected to (frequent) periodic major load excursions separated by a small number (10-50) of varying subcycles. It is important to note that a typical mission loading spectrum to which gas turbine engines are subjected bears little resemblance to that experienced by air frames, and therefore different predictive tools are required for each (Reference 7).

Referring again to Figure 8, it is seen that accurate propagation predictions constitute a necessary, but not sufficient, condition for the implementation of Retirement for Cause. The other requisite technology is high reliability nondestructive evaluation (NDE).

NDE must provide the means of screening disks with flaws that could cause component failure within an economically feasible RTS interval. A deterministic fracture mechanics method defines the maximum flaw size that can be missed without an in-service failure. For purposes of this study, the component life analyses were based upon deterministic fracture mechanics.

A probabilistic fracture mechanics life analysis (References 8 and 9) would use a distribution of flaw sizes. This type of analysis results in failure probability as a function of time, includes NDE reliability, and allows selection of a RTS interval to obtain an acceptable (low) failure probability with realistic NDE reliability.

2. Probabilistic Life Analysis System

Utilization of the total fatigue life of a component requires the consideration of fatigue crack propagation. The fracture mechanics approach to estimating component service life is based on the assumption that materials contain intrinsic flaws, and that fatigue failure may occur as a result of progressive growth of one or more of those flaws into a critically sized crack. Thus, the prediction and monitoring of crack growth as a function of time (or cycles) becomes one of the basic requirements of the design system. To utilize such an approach in practice requires quantitative information on component stress, materials characteristics, and nondestructive evaluation (NDE) capabilities. Much of this information cannot be defined as a single value, but must be described by a probability distribution. Two examples are: the probability that a flaw of a given size will exist in virgin material, or the probability of finding a given flaw size with a standard inspection procedure. In order to obtain a deterministic fracture mechanics life prediction (given these distributions), the conventional approach has been to use worst case assumptions for all parameters. Employing all worst case assumptions necessarily results in a conservative estimate for the service life of the component.

To circumvent this difficulty, the problem can be treated probabilistically. A closed-form solution, which takes into account all the required probabilities, is far too complex to be practicable. An alternative solution is to employ computer simulation techniques. A Monte Carlo simulator is one such technique that can be utilized to produce a component population life analysis that includes all of the related probabilities.

Monte Carlo simulators are commonly used for generating distribution functions for complex statistical problems. In this technique, probability distributions are randomly sampled to provide inputs for the simulation. This procedure eliminates the large conservative bias generated by employing worst case assumptions. Relatively large populations are examined to reduce the likelihood of incurring statistical anomalies due to random sampling. Further discussion of numerical simulation techniques, and Monte Carlo simulators in particular, can be found in Reference 10.

A probabilistic life analysis simulator was outlined in this program, but was not completed for use in the component life analyses due to time and funding constraints (component lives from the F100 Engine Structural Durability and Damage Tolerance Assessment were used). The program would utilize the Monte Carlo simulation technique and appropriate fracture mechanics. A simplified flow chart of the program and a general outline of the logic flow are presented in Figure 9.

The life analysis program can be divided into four major steps: (1) initial crack generation; (2) component inspection; (3) residual life calculations; and (4) performance evaluation and statistical update.

Step 1: The initial crack size is generated from a given log-normal distribution of flaw sizes. This distribution is defined as a function of time (or cycles), and is continually updated as the component life increases.

Step 2: The component is inspected with a probabilistically imperfect inspection procedure. Components passing inspection continue to Step 3.

Components failing inspection are rejected, and replaced with new parts so as to maintain a constant population size. Type I and Type II inspection errors, defined as passing a "bad" part and rejecting a "good" part, respectively, are also taken into account. (What constitutes a "good" or "bad" part is predetermined by the inspection interval and the safety factor under consideration.)

Step 3: The residual life of the component is calculated from a given crack growth, crack depth (a) vs cycles (N), curve. The crack growth curve is obtained by modifying the mean crack growth curve with a stress severity factor. This factor takes into account mission severity, manufacturing tolerances, machining defects, etc., and is described by a log-normal distribution.

Step 4: The residual life of the component is compared to the inspection interval to determine whether or not an in-service failure would have occurred. If failure occurs, the component is replaced in the population. If failure does not occur, a check is made to determine if the part was saved by a safety factor or a low stress severity factor. If that is the case, the crack size at the end of the inspection interval is calculated, the flaw size distribution is updated, and the processes are restarted at Step 2. If the part passed inspection, but was not saved by a safety factor or low stress severity factor, the flaw size distribution is updated, and the process is restarted at Step 1. The entire sequence of steps is repeated for the desired number of critical locations, number of inspection intervals, component population size, and required safety factors.

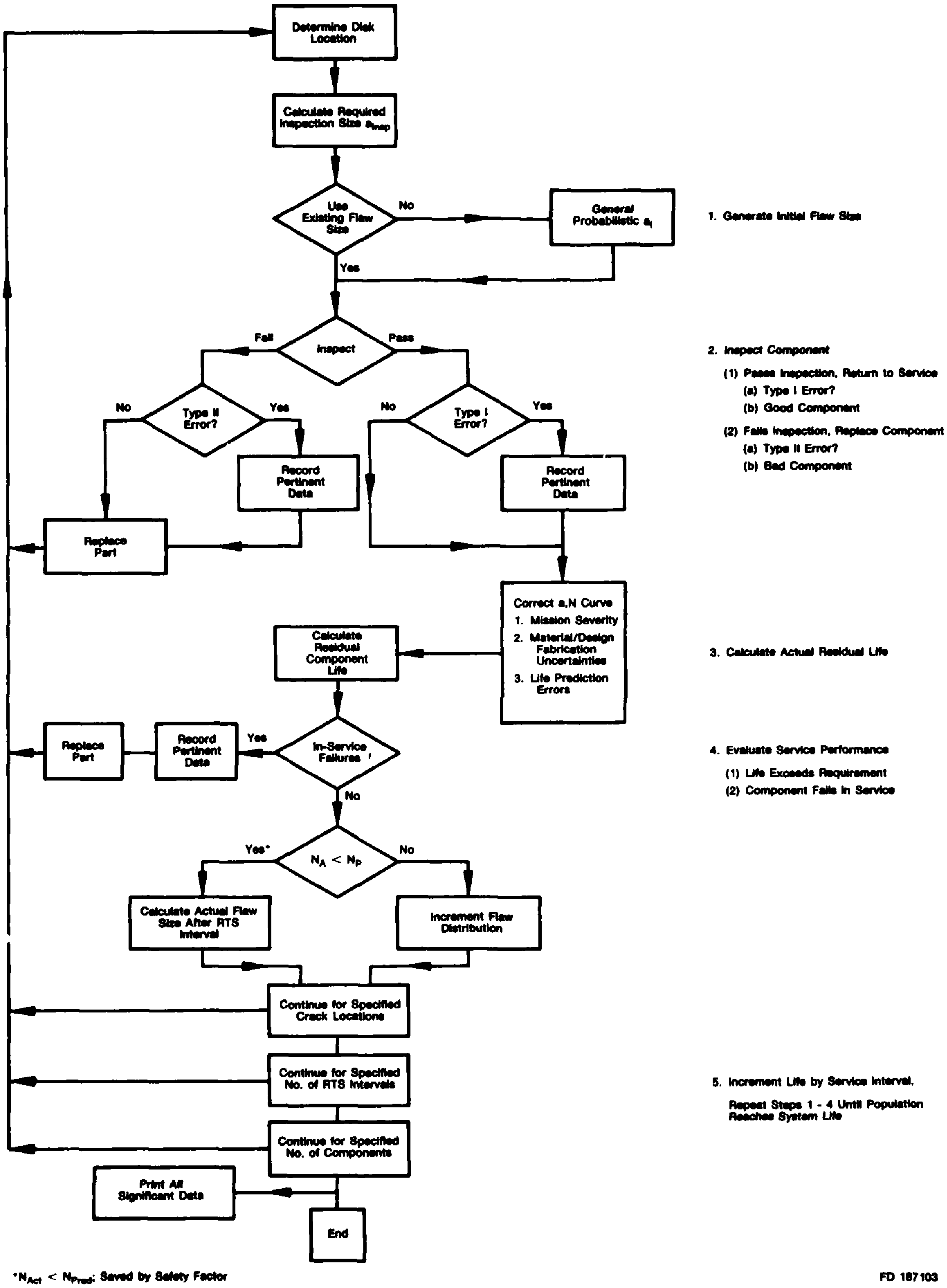

Figure 9. Flow Chart and General Logic Flow for Probabilistic Life Analysis Program

The output of the program would take the form of a table listing Type I (missed flaw) and Type II (rejected good part) errors, in-service failures, replacements, and number of inspections, all vs inspection intervals. This information can be used to ascertain the feasibility of applying RFC to a given component.

As previously stated, a deterministic fracture mechanics life analysis was used in this work as a complete component reanalysis was beyond the scope of this program. Development of the probabilistic methodology model described above was recommended by the Executive Group at the first Executive Contract Review to provide a comparison between the two methods. No additional funding was provided, however, to fully develop and exercise the model. Therefore, life comparisons were not made, as modification and refinement of this program is needed, and development of this system was not to be done at the expense of the primary analysis.

3. NDE Considerations

Insufficient NDE reliability has been a major argument against implementation of an RFC maintenance program. NDE capability with acceptable flaw detection resolution has been available for some time (Reference 11 and 12), but adequate reliability of flaw detection has been lacking (Reference 13). Complementary inspections and improvements in NDE single inspection reliability (by automation), can provide the required reliability for many gas turbine engine components to economically utilize the RFC maintenance concept.

Both the deterministic and probabilistic methods described above could provide some of the NDE reliability through multiple inspections and/or through higher NDE limits due to shorter RTS intervals. Since many NDE errors are the result of human frailty, multiple inspections and automation can enhance detection reliability. The probabilistic system outlined above has the ability to accommodate NDE reliability (probability of detection versus crack length) distributions and assess their effect upon RFC efficiency. Obviously, high reliability NDE is desired to optimize the ROI benefits of Retirement for Cause. This factor is acknowledged in the Engine Component Retirement for Cause Development Plan covered later in this report.

4. The RFC Procedure

The Retirement-for-Cause (RFC) flow chart (Figure 10) illustrates a simplified view of how this maintenance concept can be utilized. When an engine (or module) is returned for maintenance, an economic analysis is performed on the engine module (i.e., fan, compressor, high turbine, or low turbine) identified as a participant of the RFC maintenance program. If the module has already been in service for several inspection intervals, the probability of finding cracked parts may be great enough to make reinspection economically undesirable and specific components of that module are retired without being inspected. This is determined by the economic analysis at decision point one and is one of three possible decisions. An unscheduled engine removal (UER) may bring a module out of service that is more economical to return to service for the remainder of its inspection interval than to inspect and recertify it for a new full interval (the second possible decision at point one). The remaining choice at point one is to tear down the module and inspect the parts. During inspection there again are three possibilities (decision point two). If no crack is found, the part is returned to service. If the disk is found to be unsafe, it is retired. The third choice is to investigate modification or repair of a flawed part. An economically repairable part may be repaired and returned to inspection (decision point three).

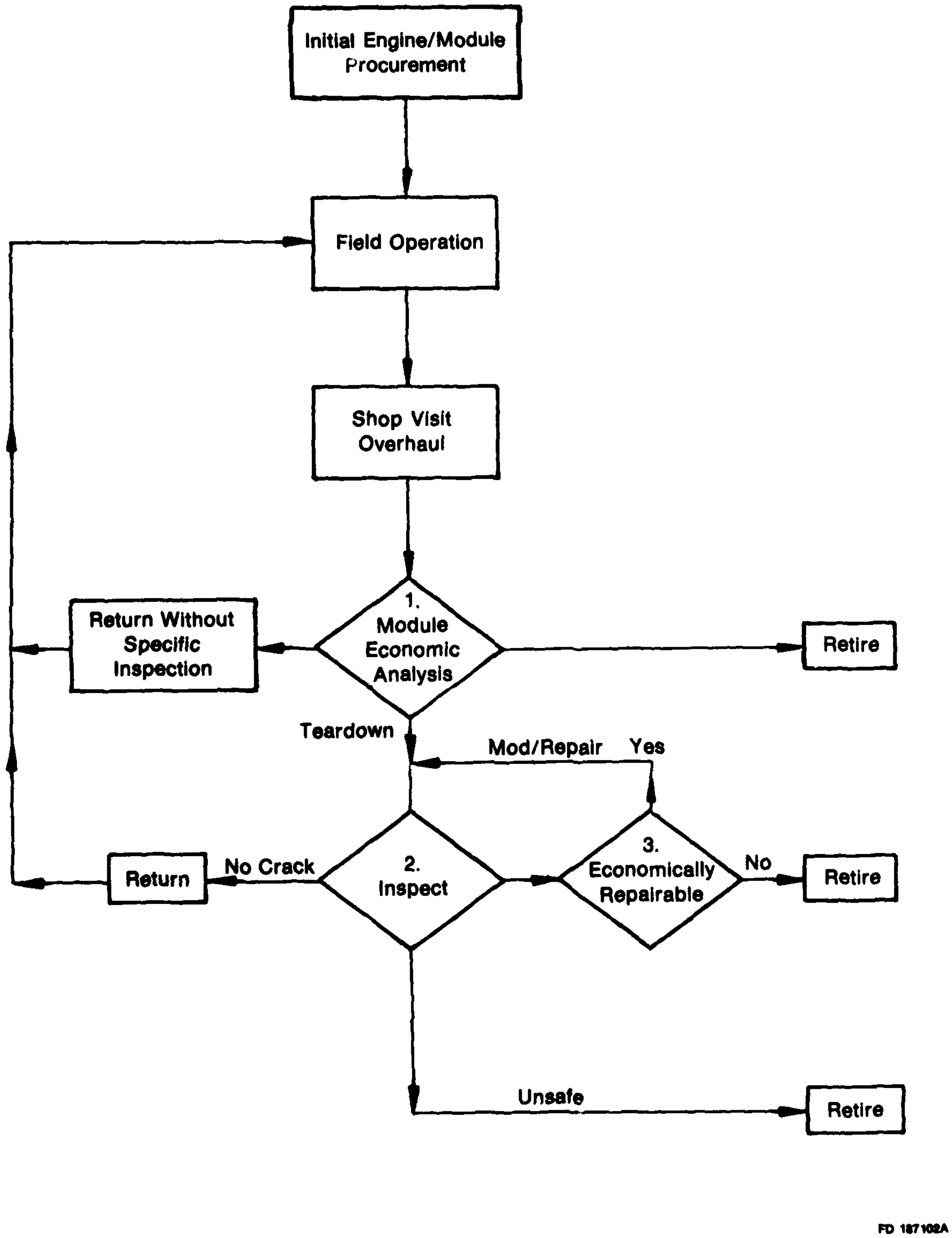

Figure 10. Retirement for Cause Procedure Flow Chart

5. Assessment of Return on Investment

Return on Investment (ROI) is an estimate of the benefits realized vs the investment required to yield those benefits. The benefit to the USAF of a RFC maintenance approach should be a reduction of the overall life cycle cost of acquiring, operating and maintaining F100 powered weapon systems. For this study, return was established as the change in the life cycle cost of the F100 engine, and the investment as the total costs associated with implementation of this concept at the F100 Engine Maintenance Center (San Antonio Air Logistics Center). Methods of calculating the ROI are discussed in Section II, E. of this report.

C. COMPONENT ANALYSIS REVIEW

The critical nature of the F100 engine to the Air Force's F-15 and F-16 weapon systems has made it important that the Air Force obtain the best possible visibility of the engine's future structural maintenance needs and component life limits as applied to each of these weapon systems. Accordingly, an in-depth structural assessment was performed on this engine by a joint Air Force/P&WA team. This effort, entitled "F100 Engine Structural Durability and Damage Tolerance Assessment" (F100 SAT) was conducted concurrently with this RFC program. It was the source of the detailed analyses, which were reviewed and the results utilized in this report.

One of the primary objectives of this durability and damage tolerance assessment was to define the inspection requirements necessary to protect the structural safety throughout the anticipated service life. A second primary objective was to establish economical modification and/or repair options for those components where it appears likely that they will be needed. This included investigating the technical feasibility of the options, defining the validation requirements, estimating the probable costs, and determining the post-modification/repair life limits and inspection requirements.

When the safety inspection requirements, the modification/repair options, and the post-modification/repair inspection requirements were defined, they were integrated into an overall force structural maintenance plan for the engine as applied to each of the two major weapon systems (the F-15 and F-16), assuming that the aircraft will be flown to their design usage/environment spectra. Because deterministic fracture mechanics analyses were used, sensitivity analyses were performed to determine the effects of probable usage/environment variations on component life limits, inspection intervals, and estimated modification/repair times. Also, these analyses determined the sensitivity of the component life limits, inspection intervals, and modification times to variation in material properties, variations in initial manufacturing quality, engine wear and deterioration, and service-induced damage. The adequacy of the engine component tracking program was assessed in light of the results of the sensitivity analyses and changes were recommended as appropriate.

The F100 SAT was concerned with assuring that critical components safely reach their life limits (as opposed to safely extending the life limits, which is Retirement for Cause). To assure this safety, a force structural maintenance plan was generated which specified component life limits and inspection intervals. This force structural maintenance plan is being implemented in mid 1980. The inspection intervals are compatible with the RFC methodology, and use of these same intervals helps minimize the impact of RFC on maintenance schedules. The component lives and inspection intervals established by the F100 SAT were utilized in this effort, and nondestructive evaluation limits for RFC were established using the F100 SAT deterministic fracture mechanics residual life analyses.

There are 47 cyclic life limited components in the F100 engine. Based upon the review of the analyses and component replacement costs, the 27 rotor components listed in Table 1 were selected as prime candidates for RFC.

This study was premised upon a 15-yr average engine life assumption. Based upon the anticipated cyclic usage rate for F-15 and F-16 aircraft, this is a maximum of 12,600 equivalent Tactical Air Command (TAC) cycles. Therefore, rotor components with life limits in excess of 12,600 TAC cycles were eliminated from further consideration. Table 3 lists, in the second column, the 21 rotor components selected for RFC. This selection is predicated upon the Bill-of-Material configuration of these components in engines as of 31 December 1979.

TABLE 3. F100 ENGINE ROTOR COMPONENTS AND NONDESTRUCTIVE EVALUATION REQUIREMENTS FOR RETIREMENT FOR CAUSE

Module	*Material*	*Component*	*Location*[1]	*Flaw Size (in.)*
Fan	Ti 6246	1st-Stage Disk and Hub	Oil Drain Slot Balance Flange Scallop Live Rim Flange Bolthole Web Bore	
	Ti 6246	2nd-Stage Disk and Hub	Web Bolthole Balance Flange Scallop Live Rim Web Bore	0.005 to 0.010 depth and >0.017 dia
	Ti 6246	3rd-Stage Disk	Live Rim Balance Flange Scallop Integral Arm Bolthole Bore	
	Ti 6246	2nd-Stage Airseal (2-3 Spacer)	Oil Drain Hole Antirotation Slot	
Compressor (HPC)	Ti 6246	4th-Stage Disk	Balance Flange Scallop	
	Waspaloy	7th-Stage Disk	Aft Flange Bolthole	
	Waspaloy	8th-Stage Disk	Web Bolthole Live Rim Bore	
	Waspaloy	12th-Stage Disk	Live Rim	0.010 to 0.018 depth and >0.047 dia
	Waspaloy	6th-Stage Airseal (6-7 Rim Spacer)	Antirotation Window	
	Waspaloy	7th-Stage Airseal (7-8 Rim Spacer)	Antirotation Window	
	Waspaloy	8th-Stage Airseal (8-9 Rim Spacer)	Antirotation Window	
	Waspaloy	9th-Stage Airseal (9-10 Rim Spacer)	Antirotation Window	

TABLE 3. F100 ENGINE ROTOR COMPONENTS AND NONDESTRUCTIVE EVALUATION REQUIREMENTS FOR RETIREMENT FOR CAUSE (Continued)

Module	*Material*	*Component*	*Location*[1]	*Flaw Size (in.)*
Compressor	Astroloy	10th-Stage Airseal (10-11 Rim Spacer)	Antirotation Window	0.010 to 0.050 depth
	Astroloy	11th-Stage Airseal (12-13 Rim Spacer)	Antirotation Window	
	Astroloy	12th-Stage Airseal (12-13 Rim Spacer)	Antirotation Window	
High-Pressure	Astroloy	1st-Stage Front Blade Retain Plate (TOBI Seal)	Knife-Edge Seal Cooling Air Hole	0.005 to 0.050 depth
	IN100	1st-Stage Turbine Disk	Rim Cooling Air Hole Integral Arm Bolthole Web Cooling Air Hole Bore	
	IN100	2nd-Stage Turbine Disk	Rim Cooling Air Hole Hub Cooling Air Hole Web Bolthole	
	IN100	1-2 Rim Spacer	Web Cooling Air Hole Radial Cooling Air Hole Radial Cooling Air Hole (w/Balance Cut)	
Fan Drive Turbine (LPT)	IN100	3rd-Stage Turbine Disk	Web Bore Knife-Edge Seal Arm-Hole Web Surface	0.038 to >0.050 dia
	IN100	4th-Stage Turbine Disk	Web Bore Web	

[1]See Figures 11a and 11b For Composite Views.
[2]Corner Flaw — Assumed Aspect Ratio (Length: Depth) 1:1
Surface Flaw — Assumed Aspect Ratio 2:1
Internal Flaw — Equivalent Flaw Diameter

D. NONDESTRUCTIVE EVALUATION REQUIREMENTS

An important parameter in a component life analysis is the initial flaw or defect condition from which the residual life is calculated. The flaw type, size, shape and location form the basis of the NDE detection requirements for RFC. This information has been compiled for the 21 RFC components of the F100 rotor, and is keyed to the force structural maintenance plan inspection intervals established by the F100 SAT. These requirements are also summarized in Table 3. Locations with residual lives less than 12,600 cycles are listed. Composite sketches of components and flaw types are shown in Figures 11a and 11b to illustrate typical defect parameters and nomenclature, and an actual 1st-stage turbine disk shown in Figure 11c.

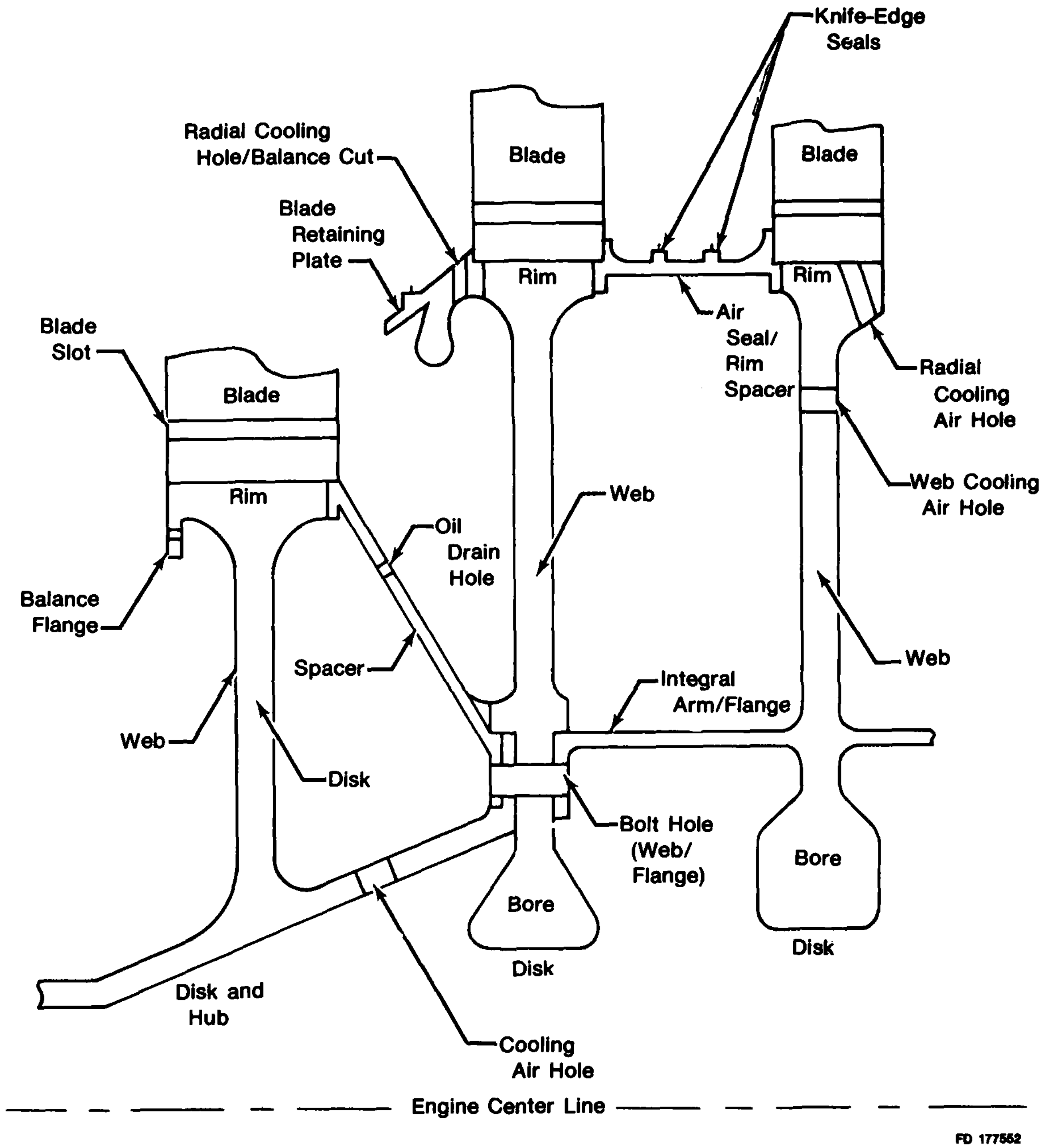

Figure 11a. Composite Sketch of Typical F100 Rotor Components and Flaw Types (Not All Features on All Parts)

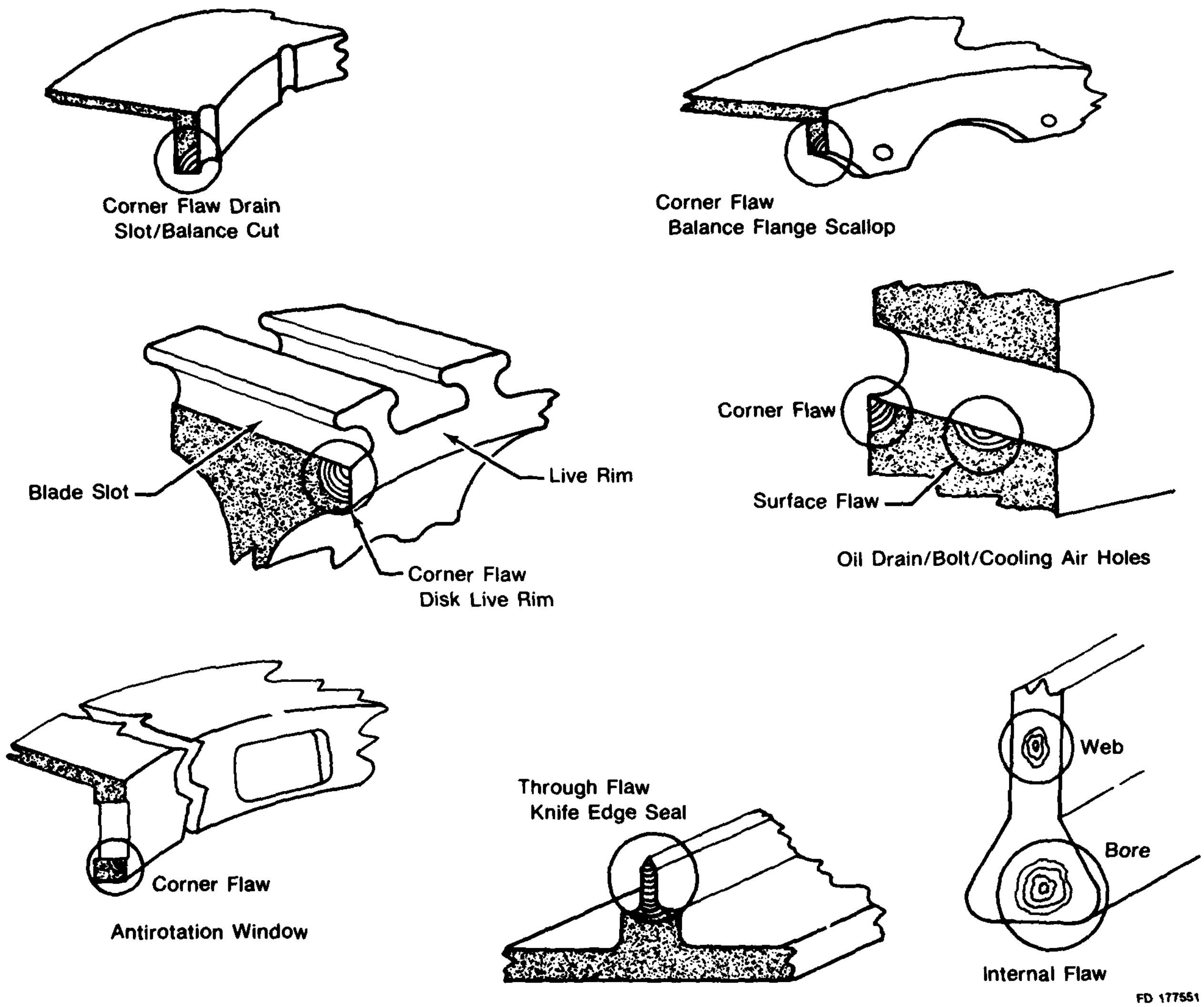

Figure 11b. Composite Sketch of Typical F100 Rotor Components and Flaw Types (Not All Features on All Parts)

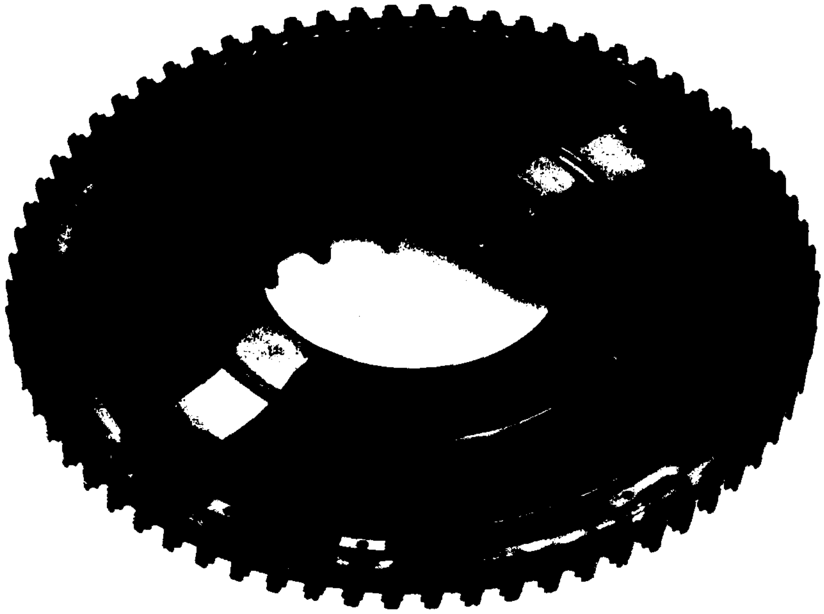

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Figure 11c. F100 1st-Stage Turbine Disk

E. ESTABLISHMENT OF DEVELOPMENT PRIORITIES

1. Introduction

The establishment of development priorities and a ranking of components for proceeding to develop and implement Retirement for Cause were based upon both economic (life cycle cost savings derived) and technical (technical risk assessments) considerations. While these concerns were evaluated for each component selected, the F100 engine is maintained on a modular basis; therefore, final ranking was done by module.

In the F100 engine, the use of similar materials within the modules results in some mitigation of the technical risk in that the development effort required for a module with relatively low technical risk is also applicable to a module with a higher risk. It is therefore difficult to isolate development to a specific module and exclude others. For example, most of the technical development effort to enable implementation of RFC for the compressor can be applied directly to the turbine modules, to yield significant LCC benefits. The establishment of LCC savings, return on investment (ROI) and component rankings are discussed in this section.

2. Life Cycle Cost Analyses

To quantify the benefits of an RFC maintenance concept for the F100 engine, life cycle cost analyses were conducted. These analyses determined the change in life cycle costs of the F100 engine that could accrue based upon implementation of an RFC maintenance procedure in January 1985 as opposed to a continuation of current or baseline maintenance practices.

An existing computer model entitled Scheduled Cost Analysis Program (SCAP) was used to calculate the differences in LCC that could be attributed to RFC. The analysis was conducted for the 21 components listed in Table 3; the components would normally have been retired prior to accumulation of 12,600 TAC cycles. This and the other ground rules and assumptions used for the LCC analysis are listed in Table 4 and were developed in conjunction with the Air Force RFC Program Working Group. While the NDE reliability assessment is unrealistic, no current studies have defined the reliability within an Air Force engine maintenance facility environment, and it is a goal that will be approached by the 1985 operational time frame.

TABLE 4. LIFE CYCLE COST ANALYSIS GROUND RULES AND ASSUMPTIONS FOR F100 RETIREMENT FOR CAUSE

Number	*Item*	*Value*
1	Average aircraft utilization life	15 years
2	Total F-15 aircraft Total F-16 aircraft	729 1,388
3	Total F100 engines in AF inventory	3,177
4	Equivalent TAC cycles/engine flight hour F-15 F-16	 2.2 3.1
5	Inspection interval	Baseline
6	Engine maintenance/development status	Mature
7	Engine production/flight schedule per engineering change proposal analysis	Baseline
8	RFC incorporation date	January 1985
9	Date of constant dollar value	1979
10	Modular removal costs	Constant
11	Depot labor costs	$30.00/hour
12	NDE reliability	100%
13	Unscheduled engine (module) removal (UER)	Baseline
14	Engine retirement about average engine service life. (7,600 TAC cycles for F-15 and 10,900 for F-16)	Normal Distribution

Once the ground rules and assumptions were established, spare parts requirements and their cost were estimated. These spare parts must be used to replace the components which will be retired (for cause) in order to maintain the same degree of fleet readiness. To estimate the spare parts cost, a scrappage rate curve was required for each RFC component. This curve was constructed as shown schematically in Figure 12. Crack propagation plots (Figure 12a) are established and utilized along with test results that describe probability of cracking vs the ratio of actual/predicted life (Figure 12b) for each of the component materials. The low-cycle fatigue life is defined as the crack initiation life (in TAC cycles) at which 1 in 1000 components contains a 0.030 in. surface length crack (0.015 in. depth). This point is used to reference the component scrappage rate curve (Figure 12c). Beyond this point, the scrap curve is based upon the probability of cracking curve of Figure 12b. Thus a scrappage rate curve for 0.015 in. depth (0.030 in. surface length) crack occurrence is established. In order to develop the scrappage rate curve for 0.005 in. deep cracks, the 0.015 in. depth curve of Figure 12c is shifted to the left by the difference in cycles (Δ) of Figure 12a, which represents the improvement in inspection capability to detect 0.005 in. deep flaws expected by the 1985 operational date for RFC.

An Internal Cost Estimation routine was developed to computerize this process. Based upon the force structural maintenance interval projected, this routine determined the number of scrapped (retired for cause) components for each interval, or the scrappage rate for each component. The scrappage rate is then converted to spare part cost and combined with depot labor costs to yield the projected scheduled maintenance costs.

If a component has a single failure mode, the scrap rate is simply read from the curve as at inspection 1, Figure 13. However, many components have multiple critical locations, which requires use of the general law of total probability. For inspection 2 shown in Figure 13,

$$p\ (a\ \text{or}\ b) = p\ (a) + p\ (b) - p\ (ab) = 1 - (p\ (\text{not}\ a) + p\ (\text{not}\ b))$$

and for inspection 3 shown in Figure 13,

$$\begin{aligned} p\ (a\ \text{or}\ b\ \text{or}\ c) &= p\ (a) + p\ (b) + p\ (c) - p\ (ab) \\ &- p\ (ac) - p\ (bc) + p\ (abc) \\ &= 1 - [p\ (\text{not}\ a) + p\ (\text{not}\ b) + p\ (\text{not}\ c)\ ] \end{aligned}$$

to establish total scrap rate for a component.

After the scrappage rates were calculated, two life cycle cost analyses were made for each of the 21 RFC components using the SCAP model. One analysis was conducted for the baseline maintenance procedure for the service life of the engine system, the other for a Retirement-for-Cause maintenance concept. The inputs to the SCAP model include: life cycle ground rules and assumptions, baseline and RFC maintenance schedules, and the incorporation date (January 1985). The SCAP model then reads the monthly production/maintenance module generation schedule, with all pre-incorporation modules following the baseline maintenance cost schedule until the first scheduled inspection after the incorporation date, at which time the modules switch to the RFC maintenance cost schedule. All post-incorporation modules follow the RFC maintenance cost schedule.

Modules/engines are retired from service using a normal distribution about the 15 yr average engine life. The 15 yr engine life is 7,600 TAC cycles for the F-15 and 10,900 TAC cycles for the F-16.

A comparison of the cumulative costs between the baseline and RFC maintenance procedures establishes the life cycle cost benefits for each component, which are totaled to yield the LCC savings due to RFC. For this study, a 0.005 in. depth detectable surface flaw was used. The life cycle cost savings total approximately \$249M and are listed by component and module in Table 5.

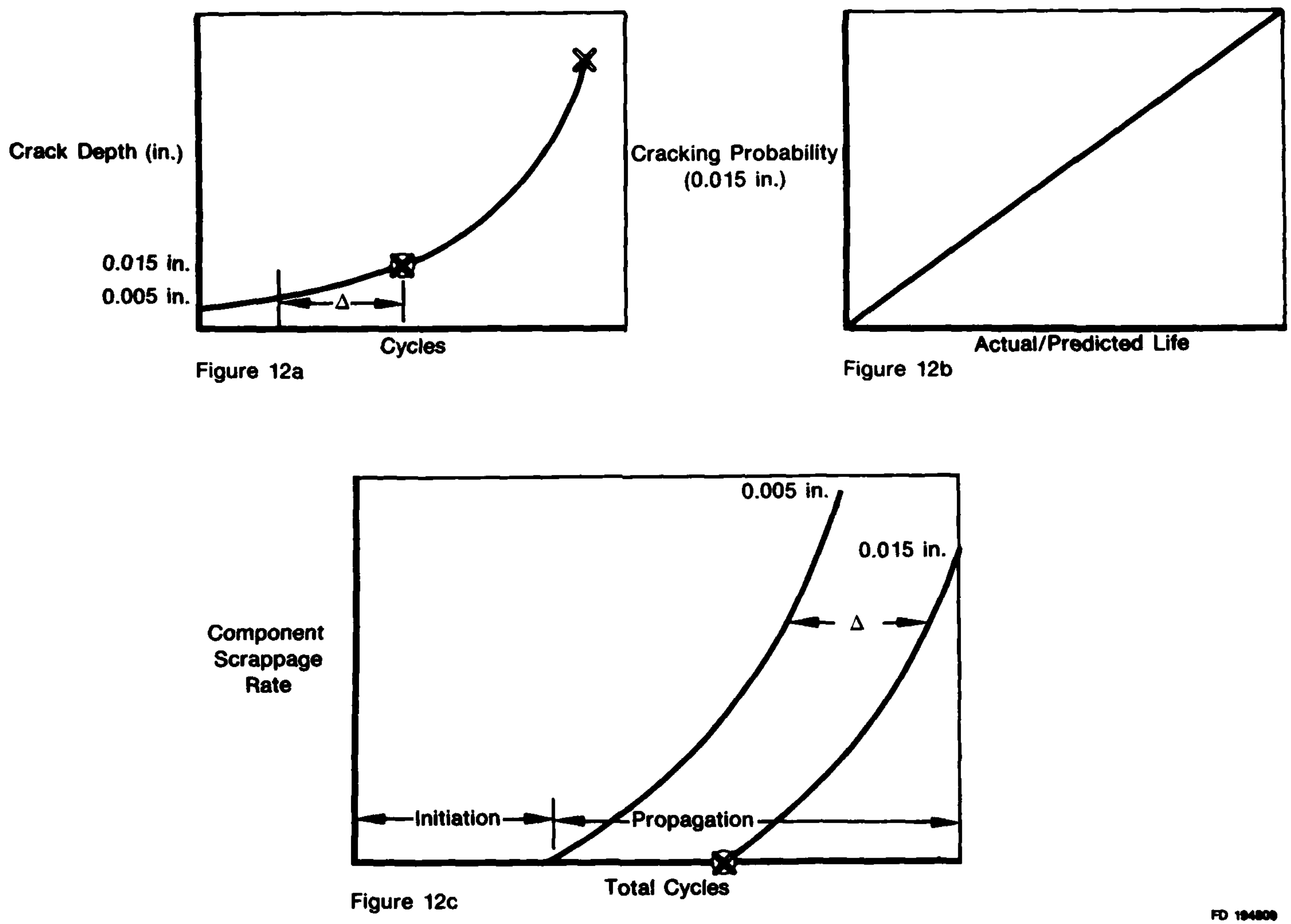

Figure 12. Scrappage Rate Curves Were Based Upon Fracture Mechanics and Historical Data for Each RFC Component

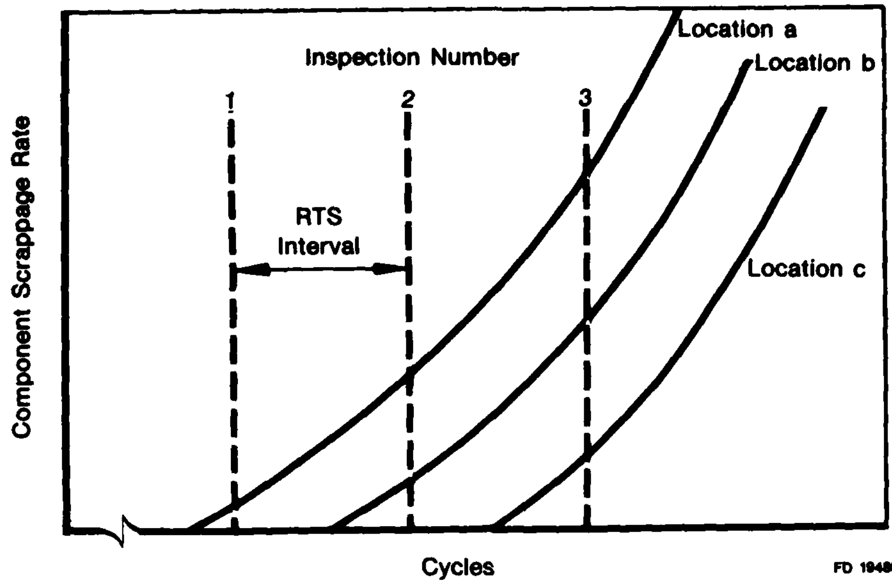

Figure 13. Scrappage Rates for Components With Multiple Fracture Critical Locations Are Established Using the General Law of Total Probability

3. Life Cycle Cost Sensitivities

This study used a 0.005 in. deep surface flaw as the basis for the LCC calculation. Sensitivity studies were conducted to assess effects of larger flaw sizes and an incorporation date change upon the LCC savings due to RFC.

The results using a 0.015 in. deep surface flaw showed an increased LCC savings from $68.3 to $71.5M for the compressor module due to not retiring disks with 0.005 to 0.015 in. deep flaws.

The fan and HPT modules could not be evaluated using a 0.015 in. flaw depth without changing the inspection interval, which would be a ground rule violation. The LPT is limited by internal defects and is not affected by changing the surface NDE limit. These results indicate that a surface flaw size (depth) three times larger than that established for this study could be used and LCC savings would still be $72.9M (compressor and LPT).

The effect of incorporation date change was evaluated using the HPT 1st- and 2nd-stage turbine disks as examples. These two components were analyzed using an incorporation date of January 1987. Comparing the results with the January 1985 results indicate about a 15% loss in savings (from $82.2 to $70.5M) due to the implementation delay. However, since these parts are among the first to reach their present retirement limits, the percentage loss for the total engine could be somewhat less than 15% for a 2-year implementation delay.

TABLE 5. F100 ENGINE COMPONENT RETIREMENT-FOR-CAUSE LIFE CYCLE COST SAVINGS

Module	Component	*F-15 Life Cycle Cost Savings — $Millions*[1]	*F-16 Life Cycle Cost Savings — $Millions*[1]	*Total Life Cycle Cost Savings — $Millions*[1]
Fan	1st-Stage Disk and Hub	12.0	17.7	
	2nd-Stage Disk and Hub	10.2	15.0	
	3rd-Stage Disk	8.4	12.5	
	2nd-Stage Airseal (2-3 Spacer)	0.1	2.4	
	Fan Total	30.7	47.6	78.3
Compressor (HPC)	4th-Stage Disk	0.1	5.0	
	7th-Stage Disk	7.0	10.5	
	8th-Stage Disk	2.1	0.1	
	12th-Stage Disk	0.1	3.8	
	6th-Stage Airseal (6-7 Rim Spacer)	0.1	1.3	
	7th-Stage Airseal (7-8 Rim Spacer)	Negl.	1.0	
	8th-Stage Airseal (8-9 Rim Spacer)	Negl.	1.7	
	9th-Stage Airseal (9-10 Rim Spacer)	1.1	1.1	
	10th-Stage Airseal (10-11 Rim Spacer)	4.7	8.3	
	11th-Stage Airseal (11-12 Rim Spacer)	4.4	7.9	
	12th-Stage Airseal (12-13 Rim Spacer)	3.4	4.6	
	Compressor Total	23.0	45.3	68.3
High-Pressure Turbine (HPT)	1st-Stage Turbine Disk	13.7	25.0	
	2nd-Stage Turbine Disk	15.6	27.9	
	1-2 Rim Spacer	1.8	12.6	
	1st-Stage Front Blade Retaining Plate (TOBI Seal)	Negl.	4.0	
	HPT	31.1	69.5	100.6
Fan Drive Turbine	3rd-Stage Turbine Disk	1.2	(1.0)	
	4th-Stage Turbine Disk	1.4	(0.2)	
(LPT)	LPT Total	2.6	(1.2)	1.4
	Total	87.4	161.2	248.6

[1]In Constant 1979 Dollars, For Period 1985 to 2000.

Since RFC LCC savings decrease substantially when implementation is delayed, it is not surprising that RFC, for a more mature engine, would produce a much smaller LCC savings. A cursory look at the RFC LCC savings for the TF30-P3 engine, which powers the U.S. Air Force's General Dynamics F-111A/E aircraft showed RFC to be applicable, but not as lucrative as for the F100 engine. This system is approximately 14 yr into its anticipated 20-yr service life and there are 520 P3 engines in the U.S. Air Force inventory. The LCC savings for the 10th- and 12th-stage compressor disks is $2.3M ($1.15M average per disk). This compares with the $7M average savings per F100 compressor disk. (A more realistic evaluation of the TF30 could be made if a more accurate aircraft mission utilization cycle was used, and all TF30 models, including Navy versions, were included.)

LCC savings are sensitive to many factors. NDE flaw size and implementation date as a function of service life were evaluated directly for the F100 engine. Implicite from the TF30 example, the following parameters also have a major impact on RFC LCC savings: number of engines in the inventory, average system life, and mission definition (cycles per engine flight hour).

4. Return on Investment Calculation

Return on Investment (ROI) is a means of evaluating the desirability of a given project or investment relative to other investments. To establish the ROI for Retirement for Cause of the USAF F100 engine, two standard methods were used: the Internal Rate of Return and the Savings to Investment Ratio.

The "Internal Rate of Return" method is defined as "the interest rate that equates the present value of the expected future receipts to the cost of the investment outlay" (Reference 14). The equation for calculating the internal rate of return is

$$\frac{R_1}{(1+r)^1} + \frac{R_2}{(1+r)^2} + \ldots + \frac{R_N}{(1+r)^N} - \left[\frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \ldots + \frac{C_N}{(1+r)^N} \right] = 0$$

or

$$\sum_{t=1}^{N} \frac{R_t - C_t}{(1+r)^t} = 0$$

where C_t is the investment capital, N is the number of years, R_t is the receipt for year t, and r is the internal rate of return. Since everything is known except r, the equation can be solved for the value of r that will cause the sum of the discounted receipts to equal the initial cost of the project. This value of r is the internal rate of return and one means of expressing the annualized ROI.

The investment required to enable operational implementation of RFC for the F100 engine in January 1985 is estimated to be $16 million (refer to Section F) and the life cycle cost savings are $249 million, both in constant 1979 dollars. The resultant ROI was calculated to be approximately 50%, if RFC for the F100 engine is implemented in January 1985 for a 15-yr period. Excluding the fan module gives an ROI of approximately 35%.

The second method of evaluation is the Savings to Investment Ratio (SIR). SIR is the sum of the annual discounted savings divided by the sum of the annual discounted investment. Using the standard discount rate of 10%, the SIR for a 1985 implementation of RFC for the F100 engine is 6.7 over a 15-yr period. If the fan module is excluded, the SIR is 6.0 for the same period.

5. Component Ranking

The selection and ranking of components was based upon three factors: life cycle cost (LCC) impact; NDE requirements; and an assessment of where the state-of-the-art in applied fracture mechanics is at this time. The first factor is economic, and the latter two are technical risk items. Basically, it reduces to two questions: How accurately can the residual life of a component be predicted; and how well can fatigue defects be detected? Also included in assessing risk were potential rework or modifications to designs of components or inspection processes under consideration which could be completed and incorporated prior to the January 1985 RFC operational date.

The final ranking was done by module because NDE requirements are similar among components of the same module and it is economically and logistically impractical to return units of less than a complete module (or modular item) to the Air Logistics Center. Table 6 ranks the modules from most to least suitable for continued RFC development/implementation effort at this time. The reasons for this ranking are as follows:

a. The compressor module is ranked first because of an attractive LCC saving along with relatively easily attainable NDE requirements. In fact, relaxation of minimum detection requirements to 0.015-in. depth (reference Table 3) would not adversely effect the LCC savings.

b. The high-pressure turbine module is ranked second because of the high LCC cost savings potential. The requirements in this module for NDE flaw detection and accurate residual life prediction are most stringent. Potential modification to the 1-2 spacer may ultimately eliminate this component from the consideration, and it is conceivable that reworks of some of the critical areas of the two disks could result in less stringent NDE requirements. At the present time, however, this module presents the greatest technical risk.

c. The fan drive turbine is ranked third based upon LCC savings. NDE requirements are not stringent, but LCC savings are the lowest for all the modules.

d. The fan module is ranked last, or has the lowest development priority. The LCC savings are very attractive, however, techniques being implemented as a part of the force structural maintenance plan established by the F100 SAT will be in place for the disks in 1983. Retirement for Cause of these disks will be an extension of these techniques (proof tests). Because the disks account for \$75.8M of the projected \$78.3M LCC savings due to RFC, and techniques will be in place prior to the RFC implementation date, the fan module was ranked last in development priority.

TABLE 6. DEVELOPMENT PRIORITY RANKING

Module	*Components*	*LCC Savings (\$Million)*
Compressor (HPC)	4, 7, 8, 12 Disks 6-7 through 12-13 Spacers	68.3
High-Pressure Turbine (HPT)	1,2 Disks TOBI Seal 1-2 Spacer	100.6
Fan Drive Turbine (LPT)	3,4 Disks	1.4
Fan	1, 2, 3, Disks 2-3 Spacer	78.3

*Ranking is from highest to lowest priority

F. DEVELOPMENT PLAN

1. Introduction

Based upon the results of the preceeding tasks, a preliminary plan was developed to identify the technology and other activities required to enable implementation and operation of RFC at an Air Logistics Center, and the time phasing necessary for a target application date of January 1985. The logic upon which the plan was developed is shown in Figure 14. There are five sequential steps inherent in this flow chart: 1) development of the required technological and management tools; 2) development of inputs and exercising/optimizing of the tools; 3) demonstration/verification of the tools; 4) evaluation and documentation of the tools and 5) implementation and use of the tools.

The activity leading to successful implementation and execution of a Retirement-for-Cause maintenance philosophy for F100 engine components is comprised of seven major phases, as delineated below:

Phase I — Concept Definition of Engine Component Retirement for Cause

Phase II — Life Assessment Systems Development

Phase III — Methodology Demonstration

Phase IV — Nondestructive Evaluation Systems Development/Scaleup for Component Retirement for Cause

Phase V — Implementation of Retirement for Cause

Phase VI — Documentation and Coordination for Retirement for Cause

Phase VII — Product Support/Sustaining Engineering Program.

The time phasing of these activities is shown in Figure 15, along with the major subtasks within phases. Phase I is considered the Concept Definition phase reported herein and is included for reference. Technical activity on several phases is concurrent to meet the January 1985 target date, and the total effort assumes a June 1980 start date.

2. Development Plan Outline

The development plan is presented in annotated outline form below for each phase:

Phase I. Concept Definition

A. RFC Methodology
B. Disk Analysis Review
C. NDE Capability/Requirements Study
D. Disk Priority Ranking
E. Road Map Development Plans.

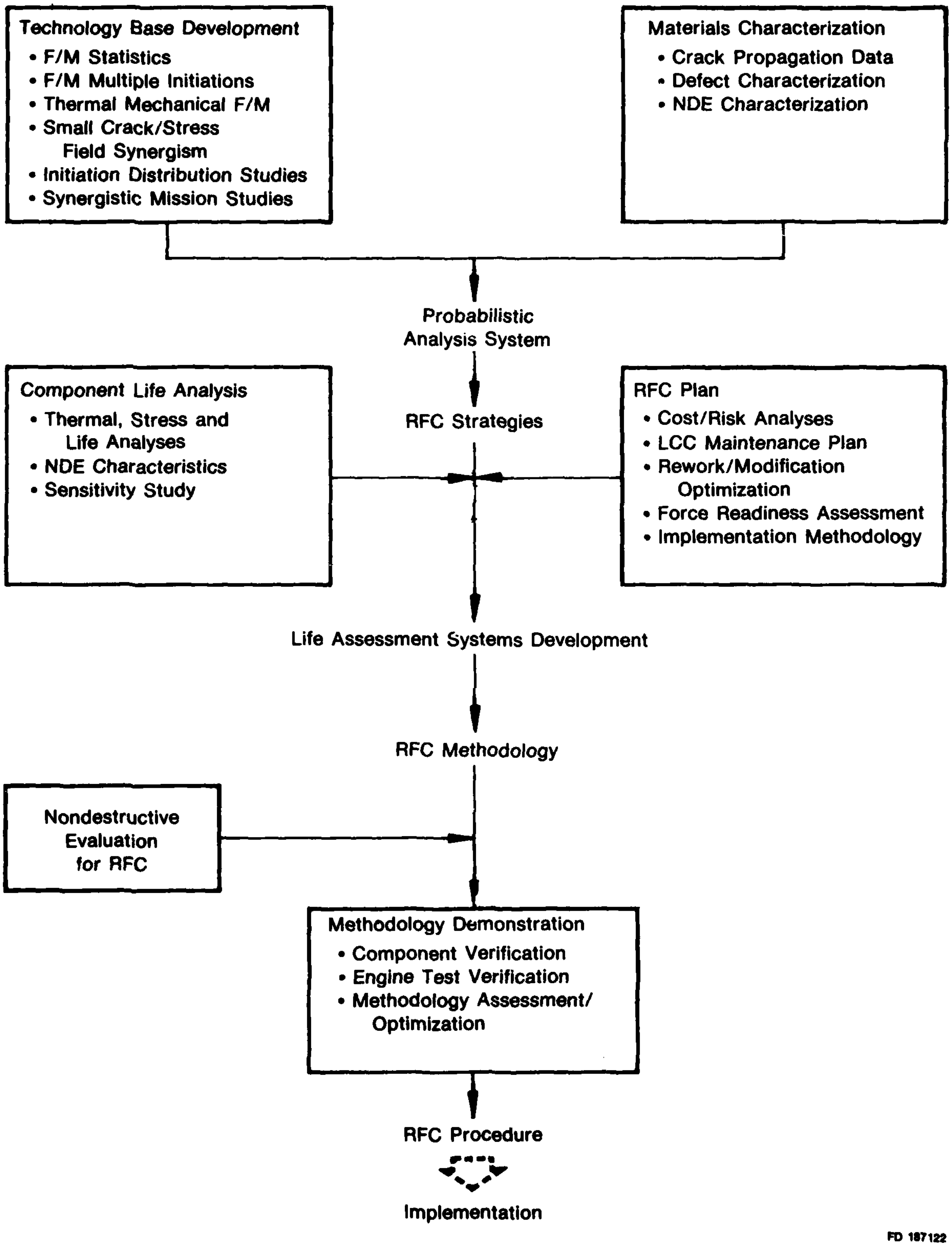

Figure 14. Technology Development Flow Chart for Engine Component Retirement for Cause

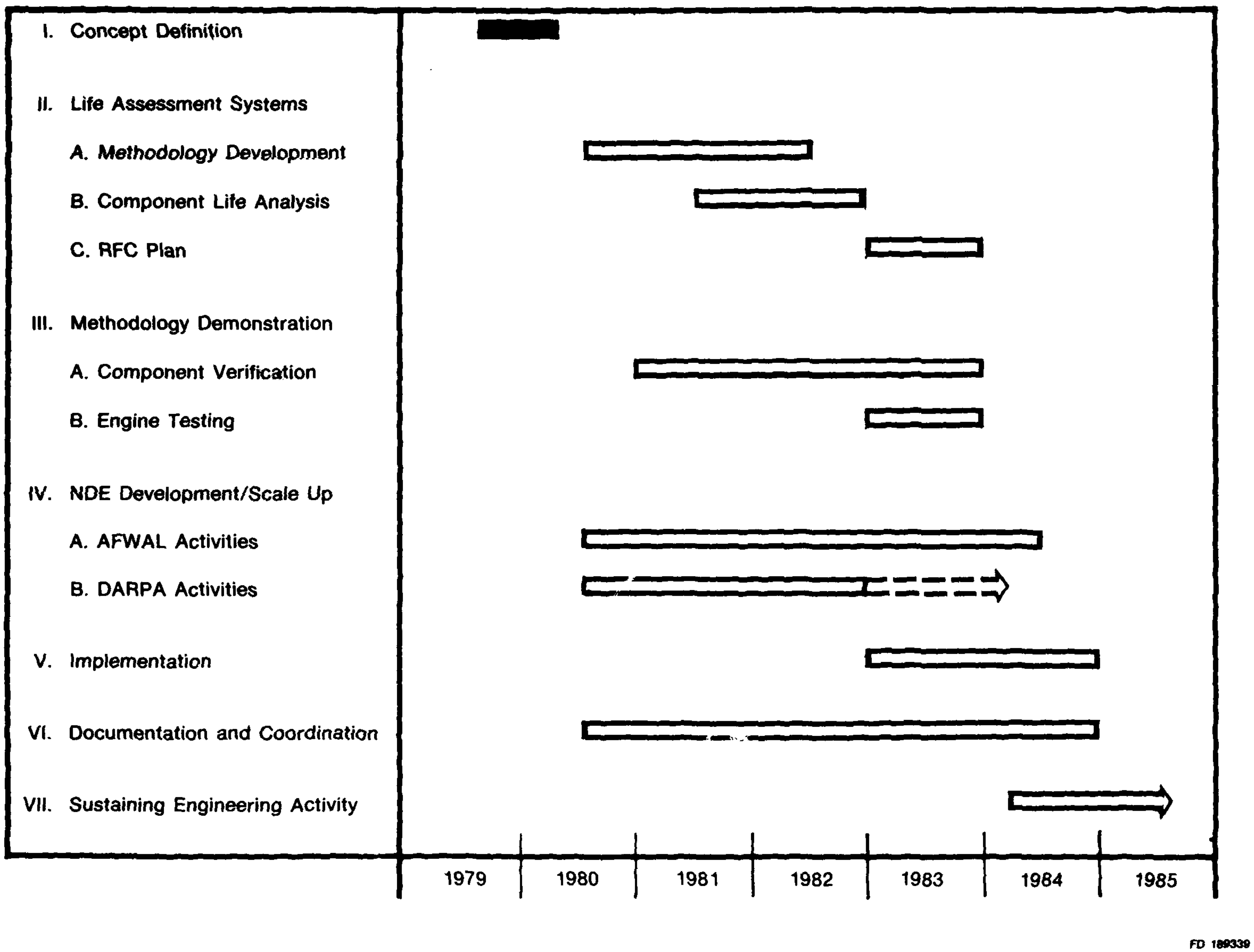

Figure 15. Development Plan Engine Component Retirement for Cause

This phase is included for reference purposes.

Phase II. Life Assessment Systems Development

A. Methodology Development

1. Probabilistic Analysis System
2. RFC Methodology
3. Technology Base Development
4. Materials Characterizations
5. Component Proof Test Concepts

B. Component Life Analyses

1. Component Thermal Analyses Review
2. Component Stress Analyses Review
3. Component Life Analyses
4. NDE Characterization Requirements
5. Boundary Condition/Sensitivity Study

C. RFC Plan

1. Cost/Risk Analyses
2. LCC Maintenance Plan
3. Rework/Modification Optimization for RFC
4. Force Readiness Assessment
5. Implementation Methodology.

The estimated phase duration is 42 mo, with an estimated completion date of January 1984. This phase would provide the key technology foundation for this RFC Concept. As such, it would establish the generic basis for application of RFC to other systems.

Phase III. Methodology Demonstration

A. Component Verification

1. Component Testing
2. NDE System Assessment
3. Failure Mode Documentation

B. Engine Test Verification
C. Methodology Assessment/Optimization

The estimated phase duration is 36 mo, with an estimated completion date of January 1984. Engine testing is anticipated to be concurrent with testing conducted under the F100 Component Improvement Program, and therefore, some adjustments in schedule for item B. above may be required.

Phase IV. NDE System Development/Scaleup

A. AFWAL/M Activities
B. DARPA Activities

The Nondestructive Evaluation System development and scaleup to support Retirement for Cause will be the subject of an Air Force Wright Aeronautical Laboratories/Materials Laboratory (AFWAL/M) contract program procurement. This procurement will result in a prototype NDE system of modular construction, with generic capability that will be evaluated in an Air Logistics Center environment. After this evaluation, an appropriate number of systems will be installed at the San Antonio Air Logistics Center. Estimated phase duration is 48 mo with an estimated completion date of June 1984.

The Defense Advance Research Projects Agency (DARPA) activities are expected to address advanced concepts for possible incorporation as modules of a second generation system.

Phase V. Implementation

A. ALC Activities
B. Product Support Activities

Implementation is the primary responsibility of the Air Logistics Center, with Product Support Activities provided by the supplier of the NDE system and the Pratt & Whitney Aircraft Group F100 Product Support Organization, as required.

Estimated phase duration is 24 mo, with an estimated completion date of January 1985, the target date for the Retirement-for-Cause maintenance system to be operational for the F100 engine.

Phase VI. Documentation and Coordination

A. Executive Reviews
B. Contractor Activities Coordination
C. Technology Documentation
D. F100 Program Coordination
E. Air Force Command/Agency Coordination
F. Final Documentation Reports

The estimated phase duration is 52 mo with an estimated completion date of January 1985.

Phase VII. Sustaining Engineering Activity

This phase begins prior to the January 1985 RFC operational date and continues, as required, throughout the remaining operational lifetime of F100-powered weapon systems.

3. Estimated Development Costs

In order to calculate a return on investment, estimates of development costs were made for each phase. These rough order of magnitude estimates were made in conjunction with the AFWAL Working Group and include both development and facilities costs. Table 7 presents the estimated cost breakdown for the period 1980 through 1985. The total does not include the buildup-run-teardown costs associated with the engine demonstration tests, but does include RFC technology support costs for that engine test.

TABLE 7. ESTIMATED DEVELOPMENT COSTS — RETIREMENT FOR CAUSE

Phase	Item	Estimated Costs $ Million
I	Concept Definition	0.15
II	Life Assessment Systems	2.10
III	Methodology Demonstration	1.50
IV	NDE System Development	4.00
V	Implementation	3.00
VI	Documentation and Coordination	0.70
VII	Sustaining Engineering Activity	N/A
	Specialized Facilities/Equipment	4.50
	Total Estimated Costs	15.95*

*Rounded to $16M for calculations.

Estimated costs for Phases I through IV and Phase VI are based upon relatively complete analysis of requirements. The Phase V, Implementation costs are an estimate arrived at during discussions between the AFWAL and SAALC working groups. Phase VII, Sustaining Engineering Activity was not estimated, as it would be absorbed into the normal Product Support Activity.

The specialized facilities and equipment estimate includes the cost of the proofing facilities for the fan disks which will be in operation in the 1983 time period and will be utilized for RFC, and estimated costs of peripheral equipment/facilities for NDE and other RFC peculiar requirements.

SECTION III

CONCLUSIONS

The application of a Retirement-for-Cause maintenance approach to the F100 engine is feasible and will result in significant LCC savings over the life of the engine system. This study has identified LCC benefits of $249 million (15-yr basis), and estimated costs to fully implement this concept at $16 million. To realize maximum benefits, development of RFC should begin immediately to assure meeting the January 1985 target operational date.

The benefits of RFC established in this study were based upon deterministic component life analyses. While RFC could be implemented based upon deterministic methodology, benefits would not be optimum. A probabilistic methodology would provide information, such as cost/risk analysis, in a form to enable management decisions to be made with the highest probability of optimizing both the success and benefit of the Retirement-for-Cause maintenance concept.

Two additional observations can be made: The methodology and procedures followed and described herein are applicable to systems other than the F100 engine. A cursory review of other P&WA engines revealed that the RFC maintenance concept is generic and has direct applicability to rotor components of those engines. In fact, the methodology has broad applicability to other engine components, and indeed, to systems other than aircraft gas turbine engines.

The decision to apply RFC to other components or systems would be based upon economic factors, predicated upon the remaining anticipated service life of that system. This study was based upon a 15-yr average engine/weapon system life. Should the actual system life exceed 15 yr, additional benefits occur due to two factors: application to additional components whose life limits are in excess of 15 yr (12,600 TAC cycles), and continued accrual of LCC savings on the 21 components already selected.

The other observation is that the utilization of Steering and Executive Group program reviews was very beneficial in achieving the objectives of this effort, and this operational procedure is recommended for future programs of similar scope and implication.

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LIST OF SYMBOLS

AFWAL	Air Force Wright-Aeronautical Laboratories
ALC	Air Logistics Center (Command)
AMT	Accelerated Mission Test
F100 SAT	F100 Engine Structural Durability and Damage Tolerance Assessment (F100 Structural Assessment Task)
HPC	Compressor (High Pressure)
HPT	Compressor Drive (High Pressure) Turbine
IR&D	Independent Research and Development
LCC	Life Cycle Cost
LCF	Low Cycle Fatigue
LPT	Fan Drive (Low Pressure) Turbine
$M	Millions of Dollars
NDE	Nondestructive Evaluation
RFC	Retirement for Cause
ROI	Return on Investment
RTS	Return to Service
SAALC	San Antonio Air Logistics Center
SCAP	Scheduled Cost Analysis Program
SER	Scheduled Engine Removal
SF	Safety Factor
SIR	Savings to Investment Ratio
TAC	Tactical Air Command
UER	Unscheduled Engine Removal
USAF	United States Air Force

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